PILE-UP FREE PARAMETER ESTIMATION AND DIGITAL ONLINE PEAK LOCALIZATION ALGORITHMS FOR GAMMA RAY SPECTROSCOPY

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Abstract

A fast waveform sampling facility has been recently developed and integrated into the VAX-based data acquisition system at the Energy Research Laboratory (ERL). This study uses the above facility in developing algorithms for digitally determining the basic pulse parameters and tackling the problem of pulse pile-up in Gamma-ray spectroscopy. A number of parameter estimation and digital online peak localisation algorithms are being developed, including a pulse classification technique which uses a simple peak search routine based on the smoothed first derivative method, which gave a percentage error of peak amplitude of less than 0.1. A finite input deconvolution filter of 3 coefficients and 4 coefficients have been tested successfully to resolve pile-up to an average percentage of 93% and 92% pile-up free respectively. The classification technique has the unique feature of cutting down the computation largely by only allowing the event of interest to be executed by a particular algorithm. The pulse classification technique was tested successfully on a TMS320C6000 high performance floating-point processor to give an execution time down to 2 msec.

1. Pulse pile-up in Gamma-ray spectroscopy

A common problem in nuclear spectroscopy is pulse pile-up caused by the non-zero response time of the detection system. For germanium detectors, the time required to collect all the ionisation current associated with an event ranges from 0.5 to 6.0 μs [4]. The fact that pulses from a radiation detector are randomly spaced in time can lead to interfering effects between pulses when counting rates are not low. These effects are generally called pile-up and can be minimised by making the total width of the pulses as small as possible.[6]. Pile-up phenomena are of two types. The first type is known as tail pile-up and involves the superposition of pulses on the long duration tail from a preceding pulse (see Fig 1).

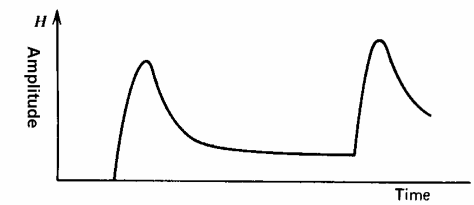

Figure 1. pile-up effect on a pulse peak from the tail of a preceding pulse

Tails can persist for relatively long periods of time so that tail pile-up can be significant even at relatively low counting rates. A second type of pile-up is the peak pile-up, which occurs when the mutual pulse spacing between the two overlapping pulses is less than approximately $\tau_R/2$ where τ_R is the mean total width of all pulses. Researchers often simply reject pile-up, when it is recognised [3]. In our case, we do not wish to lose the information associated with such events, but we propose to reject peak pile-up since it occurs less frequently than tail pile-up in nuclear spectrometry, so we use a window-based pulse classification technique, knowing the typical pulse width (Full Width Half Maximum) of Gamma-rays to classify single pulses from piled-up and separate pulses. The classification technique uses a simple peak search routine which uses the first derivative method to detect a peak, and rejects peak pile-up, since its probability of occurring in our events is only 7%. Pile-up probability of occurring is around 51%, remaining records are single and two separate pulses. The classification technique cuts down the computation largely by processing only tail pile-up.

2. Peak detection using deconvolution

A linear time-invariant system takes an input signal x(n) and produces an output signal y(n), which is the convolution of x(n) with the unit sample response h(n) of the system.

In many practical applications we are given an input signal x(n)= xd(n)+ xi(n), where xd(n) represents a desired signal sequence and xi(n) represents some undesired interference or noise component, and we are asked to design a system that will suppress the undesired interference component. In such a case, the objective is to filter out the additive interference and noise while preserving the characteristics of the desired input signal xd(n).

There is another class of problems which exist in nuclear spectrometry applications and that is we are given an output signal measured from a shaping amplifier system whose characteristics are well known and modelled, and we are asked to determine the input signal. We know that the shaping system has some effect on the input pulse expressed in terms of the impulse response of the system. So the problem is to design a corrective system which, when cascaded with the original system, produces an output which is in some sense a replica of the input. In linear system theory this corrective system is called an inverse system, because the corrective system has a frequency response which is the reciprocal of the frequency response of the shaping system. Furthermore, since the shaping system gives an output y(n) that is the convolution of the input x(n) with the impulse response h(n), the inverse system operation that takes y(n) and produces x(n) is called deconvolution [6].

Many researchers have used deconvolution algorithm to reconstruct the initial detector impulse signal from the shaped CR-RC amplifier pulse. The simple CR-RC impulse response, $(t/\hat{o}).e^{-t/\tau}$, was chosen because of its good signal-to-noise ratio while it lends itself to making the deconvolution equation very simple. The ideal pulse shape, from a noise point of view, is a cusp-like pulse [7]. Gaussian and triangular pulses are almost as good, but are very difficult to build. The amplifier output after being digitised through an ADC, can be processed to yield amplitude and timing of the charge pulse from the detector. The deconvolution achieves this by forming a weighted sum of three or more samples of the amplifier output [8,9,10]. It is well known that v(t) the output of the shaping system, h(t) the impulse response of the amplifier/shaper, and s(t) the input signal, are related in the time domain by a convolution integral. This can be written

$$v(t)= \int h(t-t').s(t').dt'$$

If we sample output v(t) at regular intervals, then we can write the equation in a matrix form as

$$V_i= \sum H_{ij}S_j \qquad \text{or} \qquad V=H.S$$

The original signal impulse can be recovered by performing the inverse operation

$$S=W.V= H^{-1}.H.S$$

and the elements of the weight matrix W can be found by numerical matrix inversion of H. The transfer function for the CR-RC shaping system is:

$$\tau 1/(Ci.(1+s\tau 1)(1+s\tau 2))$$

which shows that the system is an all pole system. The impulse response of the system has the form:

$$(\tau 1)(\exp(-t/\tau 1)-\exp(-t/\tau 2))/(Ci(\tau 1-\tau 2)) \text{ for } t>0.$$

$\tau 1$ is chosen to be equal to $\tau 2$ which gives the best combination of flat pulse top and quick return to zero and corresponds to maximum signal to noise ratio. For $\tau 1=\tau 2$ the above expression be resolved by l'Hopital's rule which yields an impulse response of

$$(1/Ci\tau 1).\ t.\exp(-t/\tau 1) \text{ for } t>0.$$

The actual value of $\tau 1$ in a practical system would be set by the requirements of ballistic deficit, pile-up and noise considerations. For scintillation counters (as in our system), the value of $\tau 1$ is not usually critical and a value of 1 μs is chosen [5]. Hence the system response is described by

$$v(t)=(t/\tau).\exp(-t/\tau)$$

where the theoretical peak is expected at $t=\tau$, and the peak value = $v(\tau)=\exp(-1)$.

By matrix inversion of the impulse response matrix, it is shown that only three non-zero weights are necessary for the CR-RC and

$$S_k=w_1.vk+w_2.v_{k-1}+w3.v_{k-2}, \qquad (1)$$

with values $w_1= (1/x).\exp(x-1)$ $\quad w_2= (-2.1/x)\exp(-1)$

and $\quad w_3= (1/x).\exp(-x-1)$

where $x=\Delta t/\tau$ and Δt is the sample interval. This implies that a filter performing this operation can be constructed by forming the weighted sum of three consecutive voltage samples in time [1,2,11,12,13].

It is easily shown that for è=0, the CR-RC impulse response reaches its maximum peak = (1/ ô).exp(-1) at t = ô, and for ô = 0.5 ìsec, this value would be 0.147 , and this is the expected peak value without noise. Hence, the expected peak location without noise is at t= ô, or è+ ô if è is not zero.
Researchers showed that the 3-point deconvolution produces zero whenever all three samples are on the pulse. The only time when it is possible for the deconvolution to produce non-zero data is when either one or two samples are on a pulse, and the third is on the pedestal. This shows that It is the sample amplitude of the amplifier output which is first multiplied with w1 which determines the true value of the deconvoluted output. This single sample time unit resolution is very difficult to attain, so researchers were satisfied with double pulse resolution [17].

It has been shown by Hall that the weighting function of the 3-point deconvolution is a triangular shape response with a sharp edge corresponding to complete input reconstruction. A robust algorithm which maximises signal at the expense of some loss in time resolution is to make a sum of two deconvoluted samples.

$S_k=S_k+S_{k+1}$, where

$S_k=w_1.v_k+w_2.v_{k-1}+w_3.v_{k-2}$ and

$S_{k+1}=w_1.v_{k+1}+w_2.v_k+w_3.v_{k-1}$

This is equivalent to using an algorithm with 4 weights which are easily calculated from the three original weights [16].
The resulting weighting function is the sum of the two individual weighting functions [12]. The weighting function for a 3-point deconvolution was shown to be of triangular shape in Hall, and its importance that it quantifies effect of timing errors on deconvolution [14].
Hence, deconvolution provides a way to remove pulse broadening which was deliberately introduced by the preamplifier. Researchers at CERN used this algorithm to give them a deconvoluted pulse which was confined to only two successive non-zero samples, attaining the required timing resolution [15].

3. Peak detection in the presence of pile-up

For the purpose of removing tail pile-up only, we have evaluated the three coefficient and four coefficient deconvolution in this context. In order to be able to cut down the computational complexity of the pile-up processing techniques, we have to look at the case of peak pile-up in a more qualitative manner. If we assume the pulse width to be approximately equal to τ_R which is approximated from our real Gamma-ray pulse records as 3 τ, where τ is the time constant of the pulse, then we will reject all overlapping pulses whose mutual separation is less than τ_R /2 as mentioned in section 1 . See figure 2 for the effect of varying degrees of overlap on the pulse pile-up.

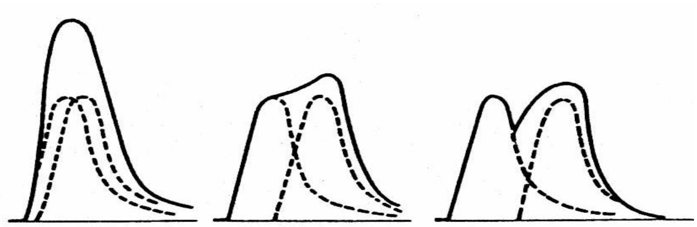

Figure 2. Shows effect of varying degrees of overlap on the Gamma-ray pile-up

An extensive study was made on simulating a pile-up of two superimposing events of same height and separated by varying displacement in time from d=τ/10 (complete overlap) to d=7τ (Complete pulse separation). It is well known that in tail pile-up the amplitude of the first pulse is not distorted while the amplitude of the second pulse is distorted. However, when the pulse separation is less than the peaking time τ , a complete overlap occurs in which the two pulses appear as one distorted pulse of double the original amplitude. This phenomenon has been verified by simulating the pile-up of two pulses separated by less than τ. See figure 2.
By observing the simulation carefully, we found that starting from a pulse separation of τ_R/2 which is equal to 3τ/2, the first pulse amplitude is preserved while the second pulse amplitude is distorted, and this occurs at a sampling index of 52ts, where ts is the sampling interval. Figure 3 shows the case where pulse separation is equal to 7τ corresponding to full pulse separation, and the pulse height spectrum for varying degrees of pile-up ranging between full pulse overlap to full pulse separation. The 7τ value can be considered as the pulse separation threshold below which pile-up occurs. The histogram shows clearly the effect of pile-up in broadening the spectrum.
By comparing the simulated results and the real scenario results, we conclude that both the simulation and the real results agree in the capability of 3-point deconvolution and the 4-point to resolve tail pile-up except in some few cases where the time separation of the two events is less than τ_R /2 which is categorised as a peak pile-up and best rejected. Researchers have already proposed a number of pile-up rejecter circuits which can easily be incorporated into the whole pulse analysis system [18].
It is very clear from the results that the amount of noise present in the real gamma events is very minimal except for the baseline region which falls outside the useful range of pulse waveform analysis. This is due to the analogue filtering stage present in the ERL set-up

before the digitiser which is responsible for filtering out all the noise contributing from the detector and amplifier. Taking into account the 45% statistics of existing tail pile-up, the 3-point deconvolution technique applied to tail pile-up events digitised at the ERL facility, succeeded in resolving pile-up by attaining a performance of 93% , which means that 93% of the events after deconvolution are pile-up free. Compared to the 4-point deconvolution, the 4-point deconvolution attained a performance of 92% .

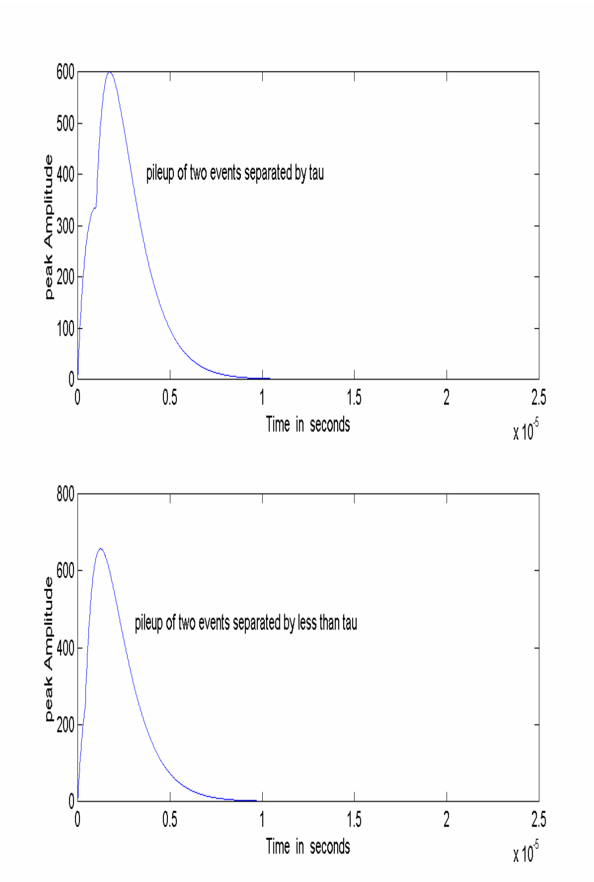

Figure 3. Peak pile-up of two simulated pulses for the case of pulse separation less than τ and equal to τ.

The 3-point deconvolution algorithm took 0.5 sec when run on a Pentium II machine of 350 MHz speed and limited to the effective window of 10%-10% of the pulse width pointed in the pulse classification technique explained earlier, a reduction of 86.8% over the time it took to process the whole pulse wave. The pulse classification technique has been tested on a TMS320C67 DSP processor running on a 150MHz speed using the C code composer for real time analysis. Using a number of optimisation stages the classification technique plus the moving average and time series analysis for estimating the pulse parameters took approximately 2 ms, giving a throughput of 486 events per second without losing information.

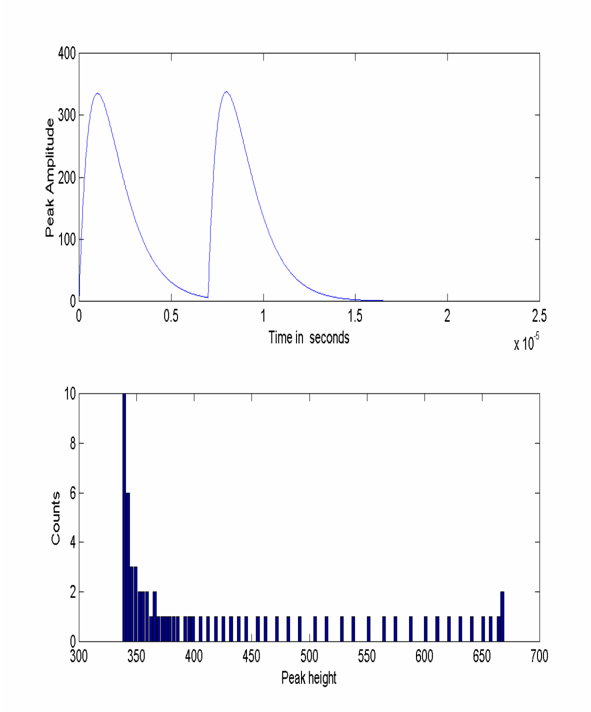

Figure 4. Pulse-height spectrum of varying degree of pulse pile-up.

4. Conclusions

A number of parameter estimation and digital online peak localisation algorithms are being developed for the purpose of Gamma-ray pulse identification in absence of noise and pile-up. A 3-point and 4-point deconvolution techniques have been successfully tested and compared and found to resolve pile-up up to 93% and 92% respectively. The slight difference in performance is attributed to the fact that the 3-point deconvolution has a better time resolution than the 4-point deconvolution which was clearly shown in both simulated and real data. A window-based pulse classification technique including a peak search routine has been devised to classify single and double pulses and reject peak pile-up giving a large reduction in computation time. The pulse classification technique was tested on a TMS320C67 high performance floating-point DSP processor with execution time down to approximately 2 ms. Work is under progress to utilise the full performance capabilities of the TMS320C6000 processor to meet all the real-time requirements of Gamma-ray Spectroscopic systems.

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